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# Evaluating the interplays among economic growth and energy consumption and $CO_2$ emission of China during 1990–2007

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The interplays among economy and energy and environment have been widely concerned. This paper put forward several indicators to quantify the relationships among economic growth and energy consumption and $CO_2$ emission. As an example, these indicators were applied to evaluate the comprehensive performances of China during 1990–2007. The results show that Chinese people has been living a better life with Chinese rapid economic growth but not synchronously in urban and rural areas. Non-carbon energy resources share has increased; however, fossil energy resources have still acted as the main driver for Chinese economic growth during this period. Technical progress has improved the fossil energy efficiency of Chinese economic activity, which leads to $CO_2$ emission per unit GDP and $CO_2$ emission per capita unit GDP dropping simultaneously; however, the two indicators' annual decline rates become smaller and smaller, which reflects that technical progress' role is dropping and economic scale's effect is climbing. People's survival has a rising contribution to $CO_2$ emission. $CO_2$ emission per capita has increased, which shows that economic scale has greater impact on $CO_2$ emission than technical progress does. Relatively speaking, Chinese development patterns have become more and more sustainable during this period. Finally, based on the related issues being discussed, some corresponding suggestions are put forward for Chinese government to further coordinate the relationship among economic development and energy consumption and $CO_2$ emission. The proposed indicators can form a set of useful tool for policy-makers to promote the harmonious development of economy and energy and environment in different regions and countries.



**Contents**



## 1. Introduction

China has been enjoying the world's fastest economic growth by a 9.9% annual growth rate of gross domestic production (GDP) or a 8.6% annual growth rate of per capita GDP since Deng Xiaoping implemented the 'Open Door Policy' in 1978 (see Fig. 1), in comparison with the world's average of 3.3% during the same period. Nowadays, China has become the fourth largest economies or even the second largest economy in terms of purchasing power parity [1]. And rapid growth in GDP since the 1980s has made China the third-largest exporter in the world as of mid-2006 [2].

According to the physical and human sciences as well as economic theory, it is energy that makes the world go around. Economic output (consumer goods and capital) is the result of

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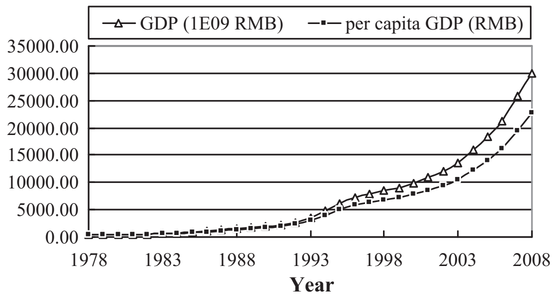


**Fig. 1.** The trend of GDP and per capita GDP during 1978–2008. *Data source*: China Statistical Yearbook (2009) [5].

mankind's ability to harness energy and to convert it to "forms" that satisfy human needs [3]. And Nel and Cooper [4] thought that economic output was explicitly derived from energy consumption (directly and indirectly). Due to economic development and increasing urbanization in the past decades, more and more energy resources in China are being consumed. From 1978 to 2008, China's energy consumption increased from 571.44 to 2850.00 million metric tonnes of standard coal equivalents (tce) (1 tce = 29,301 MJ). Now, China is the second largest energy consumer in the world. China's coal consumption was 1957.95 million tce in 2008, and the country remained self-sufficient in coal consumption, with coal output reaching 1994.20 million tce. On the other hand, China consumed 365.70 million tonnes of crude oil in 2007, while its oil output was only 186.32 million tonnes. China's dependency on oil imports stood at 49% in 2007 [5].

Energy, including renewable energy and geologic storages, is an essential input to all forms of economic and social activities. Energy system plays an important role in the economic and social development of a country and the living quality of people [6,7]. The major energy demand of fossil fuels has major consequences around the world. A main environmental problem is the emission of toxic chemical pollutants, greenhouse gases (GHGs) like $CO_2$ and other air pollutants [8,9]. These cause climate change and environmental pollution of air, land and water, which has a negative impact on the health and the living quality of humans [10].

Therein, climate change caused by GHGs has been recognized as a serious environmental problem [11]. GHGs are defined by their radioactive forcing, which changes the Earth's atmospheric energy balance; typically, expressed as watts per square meter ($W\,m^{-2}$) [12]. A positive value indicates an increase in the level of energy remaining on the Earth, while a negative value indicates an increase in the level of energy returning to space [13]. And carbon dioxide, $CH_4$, and $N_2O$ are long-lived in the atmosphere and are the major contributors to positive increases in radioactive forces [12]. Of the three main gases that are responsible for the potential greenhouse effect, $CO_2$ has the greatest climate forcing potential [14].

If the GHGs emissions continue to climb, the global average temperature is expected to rise up to 7 °C above pre-industrial levels, and this will bring about serious risks on global economies, stability of ecosystems and sustainable development [15]. It is now widely recognized that unless drastic actions are taken to reduce global warming, the world could be heading not only towards reduced growth but also more importantly towards environmental disaster [16–19].

Impacts of anthropogenic activity on increased atmospheric $CO_2$ concentration and global climate have been discussed for over 100 years. In 1861 Tyndall stated that $CO_2$ could effectively trap heat [20,21]. Other early work led to a better understanding of the relationship between atmospheric $CO_2$ concentration and global temperature [22–26]. Keeling [27,28] provided accurate background data on atmospheric $CO_2$ concentration, thereby improving the ability to subsequently document increases in $CO_2$ concentration. Ice core data of historical atmospheric $CO_2$ concentration demonstrated a relationship between $CO_2$ and global temperature [29–31]. Pre-industrial levels of atmospheric $CO_2$ concentration were estimated as 290–295 ppm [32]. By 1990, $CO_2$ concentration had risen to 350 ppm [33], surpassing 370 ppm at the Scripps Institution of Oceanography monitoring sites in 2004 [34]. It is predicted that the $CO_2$ concentration could reach 500 ppm by the end of the 21st century [12].

Therefore, scientific evidence for global warming is unequivocal, and the change in climate pattern is mostly contributed by the increased GHG concentrations. Human activities have led to the increasing contribution to the production of greenhouse gases (GHGs) since the advent of the industrial age [12]. The major sources of GHGs emissions are the fossil fuel combustion and human activities for power generation and industrial use [35]. And thus reducing GHGs emissions has become the most prominent international issues of the 21st century. Global environmental issues could significantly affect patterns of energy use around the world [36] through the introduction of energy efficiency measures, the technical changes, and the renewable and sustainable energy [8,37,38].

Alongside with the rapid economic development in China, the production and consumption of nonrenewable energy resources, including coal, crude oil and natural gas, has been led to serious environmental problems on both local and global scales in the past three decades [39]. China has attracted worldwide attention due to the global economic and environmental effects of its rapid economic growth during the last 30 years, with particular attention given to the country's accelerating energy consumption and resulting environmental problems [40]. As the largest national greenhouse gas emitter on an annual basis, China is being pressed by many developed countries to take on emission reduction commitments [41]. In addition, many developed countries have questioned the role that their financial support should play in paying for emissions reductions in China, and argued that China should also be contributing its own sizable financial resources for this purpose [42].

Various indicators have been developed and applied to monitor national $CO_2$ emission performance trends. For instance, Mielnik and Goldemberg [43] propose the use of a "carbonization index" (the level of $CO_2$ emission per unit of energy consumption) to assess the evolution patterns of developing countries with regard to climate change. Ang [44] shows that energy intensity (energy consumption per unit of GDP) is as useful as the carbonization index in the study of climate change. Sun [45] highlights the usefulness of $CO_2$ emission intensity in measuring decarbonization and assessing energy policies at the national level. Ang and Liu [46] carried out a cross-country analysis of energy-GNP correlation using aggregate energy and carbon intensities. Jiusto [47] put forward an indicator framework based on energy consumption and population for assessing US state carbon emissions reduction efforts. Bor [48] put forward the consistent multi-level energy efficiency indicators from the top (aggregated) to the bottom (disaggregated) level. Lee and Lee [49] researched income and $CO_2$ emission through per capita carbon dioxide ($CO_2$) emissions and real gross domestic product (GDP) per capita. Tol et al. [50] show that both $CO_2$ emission intensity and $CO_2$ emission per person can be considered as a function of per capita income. The indicators mentioned above may be interpreted as partial indicators since they can only reflect partial aspects of $CO_2$ emission performance. Therefore, those indicators are needed to be supplemented or improved so as to consider more factors, such as human' living quality, people's basic survival, and energy mix and then they can reveals the other factors related to carbon emissions deeply and form more specific suggestions for decision-makers. Recently, Zhou et al. [51] introduces a Malmquist

$CO_2$ emission performance index (MCPI), which is constructed from a total factor production perspective, for measuring changes in total factor carbon emission performance over time, but this index lacks structural indicators to reveal special aspects for related policies implication; meanwhile, as a comprehensive index, more relevant variables should be included.

Understanding the key drivers behind China's growing energy consumption and the associated $CO_2$ emission is critical for the development of global climate policies and providing insight into how other emerging economies may develop a low emissions future. The goal of this paper was to evaluating the interplays among economic growth and energy consumption and $CO_2$ emission in China from 1990 to 2007 through several proposed indicators, and then put forward some suggestions for the policy-makers.

## 2. Materials

In this paper, GDP stood for the level of economic development; per capita annual living expenditure included food, clothing, residence, household and facilities and articles and services, transport and communications, education and cultural recreation and services, health care and medical services, and miscellaneous and goods and services; the components of energy consumption mainly considers coal and petroleum and natural gas and hydroelectricity and nuclear power, and other energy sources are not considered for lacking the corresponding data in most years. The basic data on economy and energy in this paper came from China Statistical Yearbook [52], and $CO_2$ emission data came from Zhonghong database [53] and U.S. Energy Information Administration Independent Statistics and Analysis [54]. The whole country, except Hongkong, Macao and Taiwan, was chosen as the boundary of the analysis.

## 3. Methods

The relationship among energy, economic growth and global warming is illustrated in Fig. 2. Energy resources promote economic growth through driving all kinds of economic activities, and human's ordinary living requirements are also satisfied by consuming all kinds of energy resources. Therefore, human' living quality is continually improved with economic growth and their requirements being attained. Meanwhile, energy consumption during all kinds economic activities and human's ordinary living leads to all kinds of greenhouse gases emissions, and these emissions further cause global warming. In return, global warming has adverse effects on economic growth through changes in water, air and food quality and changes in ecosystems, agriculture, industry and settlements and the economy [55]. Meanwhile, human's living quality can also become worse due to food shortage caused by the effects of elevated $CO_2$ in the atmosphere, higher temperatures, altered precipitation and transpiration regimes, increased frequency of extreme events, and modified weed, pest, and pathogen pressure [56], and human health and survival being threaten through changing weather patterns (temperature, precipitation, sea-level rise and more frequent extreme events) [55]. As a consequence, there exists a complex relationship among energy, economy and environment due to energy consumption's double effect on economic growth and human's living quality. The following indicators were applied to depict this kind of interplays.

(1) Living quality index (LQI, %): in our opinions, it is necessary for mankind's survival to satisfy their basic food, clothing and housing, and then this indicator LQI can be expressed as the percent of per capita expenditure on food, clothing and housing in Per capita annual living expenditure. The lower the indicator, the higher the living quality of people is.
(2) Fossil energy use per unit of GDP (FEUPG, tce/RMB): this indicator reflects fossil energy intensity of economic activity, and it equals to the ratio of total fossil energy consumption (here including coal, petroleum and natural gas) to GDP. The bigger the indicator, the larger the fossil energy intensity of economic activity is. Therefore, it is more unsustainable for economic development.
(3) Non-carbon energy share in energy consumption (NCES, %): this indicator reflects the share of the cleaner energy sources in energy consumption, and it equals to the ratio of non-carbon energy (such as hydroelectricity, wind power and nuclear power) consumption to the total energy consumption. The bigger the indicator, the larger the share of the cleaner energy sources is. So it is more sustainable for economic development because economic activity maybe leads to less $CO_2$ emission.
(4) Per capita $CO_2$ emission (PCE, kg $CO_2$/person): this indicator can be expressed as the total $CO_2$ emission divided by the total population. $CO_2$ emission is an inevitable product during the course of industrialization, which is caused by fossil fuel consumption. Modern industry is based on consuming a large number of resources including fossil energy. Modern social life lies in occupying and consuming resources. According to the viewpoint that social development should finally serve human's development [57], the level of per capita $CO_2$ emission reflects the level of people's living quality directly and how much space is occupied by each person in different regions under the condition of low-carbon economy pattern having not being established. If new emission reduction pattern can be based on per capita $CO_2$ emission, this will fully embody all peoples' rights that they can equally utilize public resources on earth and equally survive and develop themselves, which is very helpful for supporting the development rights of those developing countries which have low emissions. Therefore, it is an indicator based on equally development opportunity. In addition, this indicator can provide carbon cost information on residents' living in different regions and countries so as to scientifically propagandize and promote $CO_2$ emission reduction.
(5) $CO_2$ emission per unit GDP (CEPG, kg $CO_2$/RMB): This indicator equals to the total $CO_2$ emission divided by GDP, and it reflects $CO_2$ emission intensity of economic growth. The bigger the indicator, the higher the emission intensity of economic activity is.
(6) $CO_2$ emission per capita unit GDP (CEPUG, kg $CO_2$/(RMB·person)): this indicator can be expressed as follows:

$$CO_2 \text{ emission per capita unit GDP} = \frac{E_i}{GDP_i \times P_i} \tag{1}$$

Here, $E_i$, the total $CO_2$ emission in $i$ year; $GDP_i$, gross domestic product in $i$ year, RMB; $P_i$, population in $i$ year, person.

This indicator reflects impact of economic growth and population on $CO_2$ emission. The bigger the indicator, the greater the impact of economic growth and population on $CO_2$ emission is.
(7) $CO_2$ emission per capita survival (CEPS, kg $CO_2$/person): $CO_2$ emission is related to environment quality and economic development; however, environmental protection serves social development [57], in which mankind's survival rights is the most important. Reducing $CO_2$ emission should be based on mankind's basic survival. According to our understanding, mankind's basic survival conditions should include food and clothing and housing. Although these basic conditions change in different nations or regions and in different periods, the three

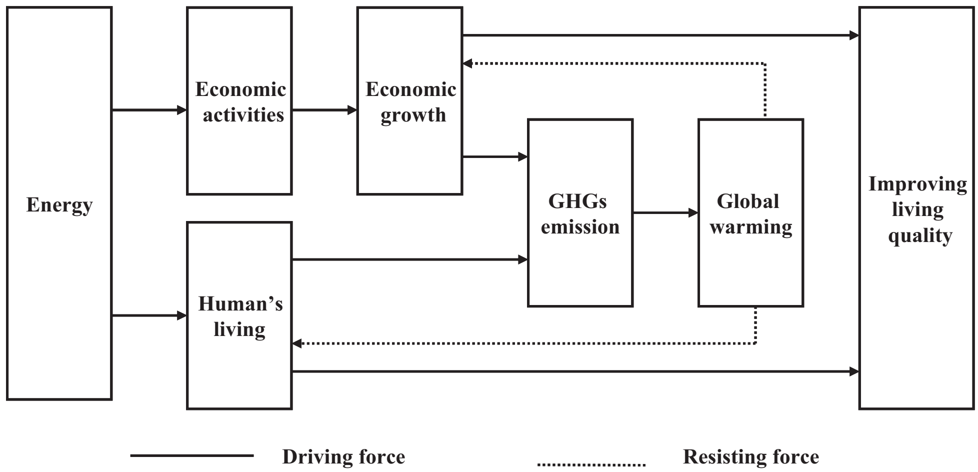


**Fig. 2.** The relationship among energy, economic growth and global warming. *Note*: Energy resources promote economic growth through driving all kinds of economic activities, and human's ordinary living requirements are also satisfied by consuming all kinds of energy resources. Meanwhile, energy consumption leads to all kinds of greenhouse gases emissions, and these emissions further cause global warming. In return, global warming has adverse effects on economic growth and human's living quality through changes in environment and social economy [55,56].

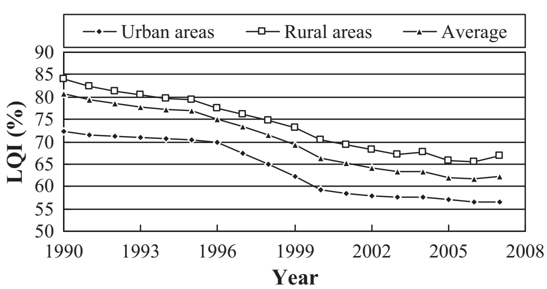


**Fig. 3.** The trend of living quality index (LQI) of China during 1990–2007. *Data source*: China Statistical Yearbook (1996–2009) [52].

aspects can reflect main parts of mankind's survival. And thus $CO_2$ emission per capita survival can be expressed as follows:

$$CO_2 \text{ emission per capita survival} = \frac{ES_i \times E_i}{GDP_i} \quad (2)$$

Here, $ES_i$, per capita expenditure on food, clothing and housing in $i$ year; $E_i$, the total $CO_2$ emission in $i$ year, kg $CO_2$; $GDP_i$, gross domestic product in $i$ year, RMB.

This indicator reflects impact of mankind's survival on $CO_2$ emission. The bigger the indicator, the greater the impact of mankind's survival on $CO_2$ emission is.

(8) Relative sustainability index (RSI): sustainable development requires that economic development and improving human's living quality should keep in harmony with resources and environment. Here, sustainable development is positively related to per capita GDP and non-carbon energy share, and it is negatively related to indicator of living quality, fossil energy use per GDP, per capita $CO_2$ emission, $CO_2$ emission per unit GDP, $CO_2$ emission per capita unit GDP, and $CO_2$ emission per capita survival. Then we defined the relative sustainability index as follows.

$$RSI_i = \frac{(PG_i/\overline{PG}) \times (NCES_i/\overline{NCES})}{(ILQ_i/\overline{ILQ}) \times (FEUPG_i/\overline{FEUPG}) \times (PCE_i/\overline{PCE}) \times (CEPG_i/\overline{CEPG}) \times (CEPUG_i/\overline{CEPUG}) \times (CEPS_i/\overline{CEPS})} \quad (3)$$

Here, $RSI_i$, relative sustainability index in $i$ year; $ILQ_i$ and $\overline{ILQ}$, indicator of living quality in $i$ year and its average value in the period studied respectively, %; $FEUPG_i$ and $\overline{FEUPG}$, fossil energy use per unit of GDP in $i$ year and its average value in the period studied respectively, tce/RMB; $NCES_i$ and $\overline{NCES}$, non-carbon energy share in energy consumption in $i$ year and its average value in the period studied respectively, %; $PCE_i$ and $\overline{PCE}$, per capita $CO_2$ emission in $i$ year and its average value in the period studied respectively, kg $CO_2$/person; $CEPG_i$ and $\overline{CEPG}$, $CO_2$ emission per unit GDP in $i$ year and its average value in the period studied respectively, kg $CO_2$/RMB; $CEPUG_i$ and $\overline{CEPUG}$, $CO_2$ emission per capita unit GDP in $i$ year and its average value in the period studied respectively, kg $CO_2$/(person·RMB); $CEPS_i$, $\overline{CEPS}$: $CO_2$ emission per capita survival in $i$ year and its average value in the period studied respectively, kg $CO_2$/person.

The higher the index, the more harmonious the relationship among economic growth, improvement of human's living quality, energy consumption and environment is. And relatively speaking, the economic activity is more sustainable.

## 4. Results

(1) Living quality index (LQI, %): as illustrated in Fig. 3, residents in urban areas have higher living quality than residents in rural areas due to dual economic structure existing in China in the long term. Chinese residents' living quality increased by 21.87%, 20.30% and 23.04% for urban and rural areas and average level respectively from 1990 to 2007, with an annual improving rate of 1.44%, 1.33% and 1.53% for the three cases during this period.

(2) Fossil energy use per unit of GDP (FEUPG, tce/RMB): as shown in Fig. 4, the fossil energy intensity of economic activity declined by 80.88% from 1990 to 2007, with an annual declining rate of 9.27% in the same period.

(3) Non-carbon energy share (NCES, %): as illustrated in Fig. 5, the share of the non-carbon energy grew by 53.66% from 1990 to 2007, with annual growth rate of 2.13% in the same period; however, the share of the cleaner energy sources still stayed less than 10% even in the later period.

(4) Per capita $CO_2$ emission (PCE, kg $CO_2$/person): as shown in Fig. 6, per capita $CO_2$ emission rose by 1.60 times from 1990 to 2007, with an annual growth rate of 5.77% in this period.

(5) $CO_2$ emission per unit GDP (CEPG, kg $CO_2$/RMB): as illustrated in Fig. 7, this indicator dropped by 78.05% from 1990 to 2007, with an annual declining rate of 8.53%.

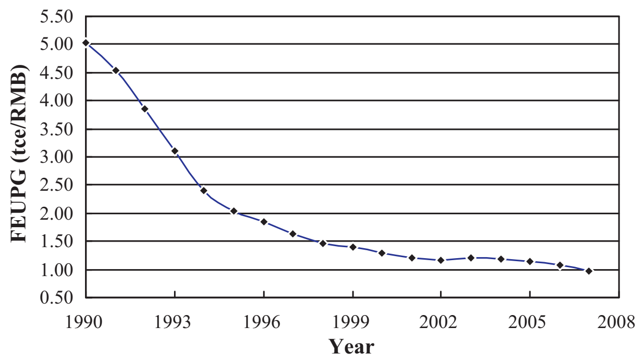


**Fig. 4.** The trend of Fossil energy use per unit of GDP (FEUPG) of China during 1990–2007.

*Data source*: China Statistical Yearbook (1996–2009) [52].

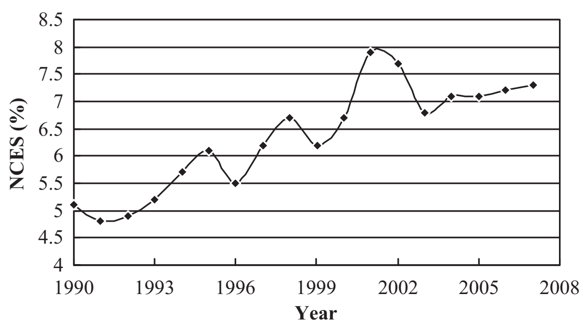


**Fig. 5.** The trend of Non-carbon energy share (NCES) of China during 1990–2007.

*Data source*: China Statistical Yearbook (1996–2009) [52].

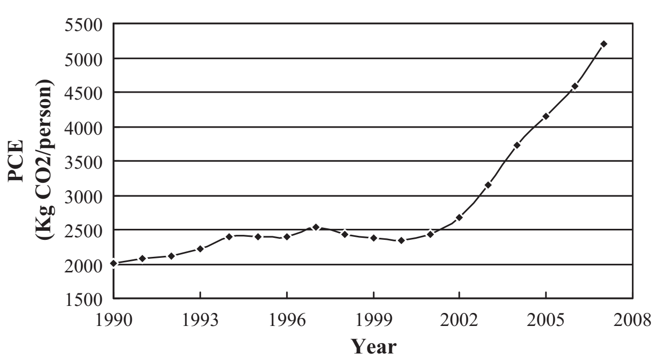


**Fig. 6.** The trend of per capita $CO_2$ emission (PCE) of China during 1990–2007.

*Data source*: Zhonghong database [53] and U.S. Energy Information Administration Independent Statistics and Analysis [54].

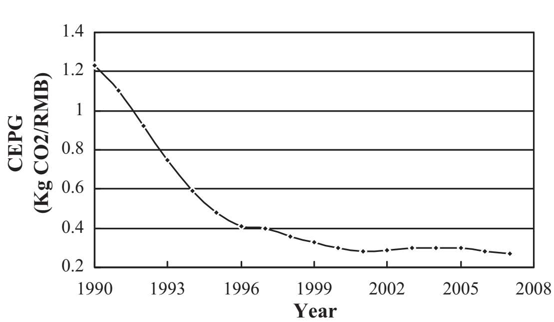


**Fig. 7.** The trend of $CO_2$ emission per unit GDP (CEPG) of China during 1990–2007.

*Data source*: China Statistical Yearbook (1996–2009) [52], Zhonghong database [53] and U.S. Energy Information Administration Independent Statistics and Analysis [54].

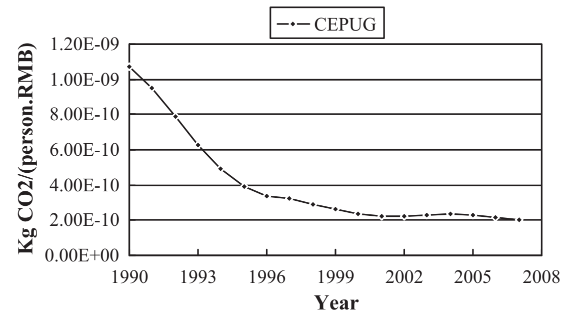


**Fig. 8.** The trend of $CO_2$ emission per capita unit GDP (CEPUG) of China during 1990–2007.

*Data source*: China Statistical Yearbook (1996–2009) [52], Zhonghong database [53] and U.S. Energy Information Administration Independent Statistics and Analysis [54].

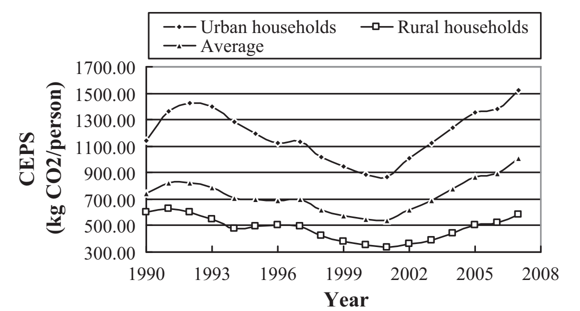


**Fig. 9.** The trend of $CO_2$ emission per capita survival (CEPS) of China during 1990–2007.

*Data source*: China Statistical Yearbook (1996–2009) [52], Zhonghong database [53] and U.S. Energy Information Administration Independent Statistics and Analysis [54].

(6) $CO_2$ emission per capita unit GDP (CEPUG, $CO_2$/(RMB·person)): as shown in Fig. 8, this indicator decreased by 81.17% from 1990 to 2007, with an annual declining rate of 9.36% in this period.

(7) $CO_2$ emission per capita survival (CEPS, kg $CO_2$/person): as illustrated in Fig. 9, this indicator rose by 34.06%, −3.52% and 35.14% for urban and rural areas and average level respectively from 1990 to 2007, with an annual changing rate of 1.74%, −0.21%, and 1.79% respectively in this period.

(8) Relative sustainability index (RSI): as shown in Fig. 10, this indicator increased during 1990–2001, then decreased from 2001 to 2005, and finally rose after 2005. And it arrived at its maximum value in 2001. Generally, this indicator grew by 924.00 times from 1990 to 2007, with an annual growth rate of 49.44% during the same period.

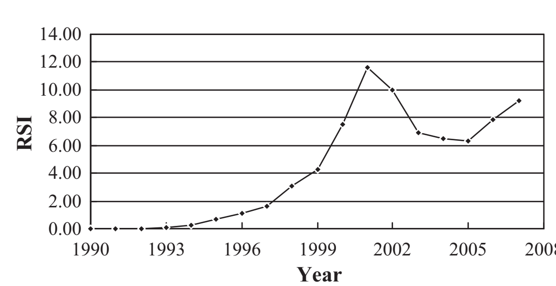


**Fig. 10.** The trend of relative sustainability index (RSI) of China during 1990–2007.

## 5. Discussion

This paper adopted several indicators to describe the interactions among economic growth and energy consumption and $CO_2$ emission. Chinese residents are living a better life from 1990 to 2007 but not synchronously in both urban and rural areas; meanwhile, this trend greatly fall behind that of Chinese per capita GDP in the same period. In fact, living quality is affected by many other factors besides economic income, such as price of commodities, and currency inflation. Therefore, those factors have greatly offset the contribution of economic growth to living quality. Fossil energy resources, especially coal, have been acting as the main driver for Chinese economic development, and technical progress has raised the energy efficiency of Chinese economy but its role decreased after 2000 due to quickly expanding economic scale and introducing some backward or eliminated technologies. As for energy mix, China will greatly depend on fossil energy resources in future although China government has vigorously developed renewable energy and nuclear energy in recent years. China's rapid economic growth is driving the increase of per capita $CO_2$ emission, and Canadell et al. [58] pointed out that the largest human contributor to the growth rate of atmospheric carbon dioxide ($CO_2$), firstly come from increasing global economic activity; however, other factors is also preventing its growth greatly, such as technical progress, and adjustment of energy mix. China made great progress in reducing $CO_2$ emission intensity of economic activity. But this trend declined very slowly after 2000. As pointed out by Wu et al. [59], China will resume an increasing trend from a lower starting point in the near future. China made great progress in reducing the impact of economic growth and population on $CO_2$ emission; however, this trend became greatly slow after 2000. Surprisingly, people's survival has increasing contribution to $CO_2$ emission, and urban residents have much greater contribution to $CO_2$ emission than rural residents during this period, which may be mainly caused by different incomes levels [60]. $CO_2$ emission per capita is generally increasing especially in the later period, which shows that economic scale has greater impact on $CO_2$ emission than technical progress does, and this is consistent with the researches of Zhang et al. [61] and Li [62]. Generally, the relationship among economy, society and environment has been greatly improved in this period although it fluctuated after 2001, and Chinese economic model is becoming more sustainable.

Meanwhile, the study also reveals that there are many potential complex issues for Chinese government to be further dealt with in future. As the largest developing country in the world, developing economy will be still one of Chinese government's main tasks. China did not take obligation to reduce greenhouse gases emission in the past. However, when facing the grim situation of global climate warming, Chinese government has actively taken commitment to cut greenhouse gases emissions in the Copenhagen climate summit in 2009. Then China cannot develop its economy any longer completely according to the past pattern, and Chinese government should take some effective measures to adjust and/or improve the present patterns of its economic and social development. Firstly, saving energy in production is still primary measure to control $CO_2$ emission due to great dependence on fossil energy resources, including taking advanced technologies and ensuring the regular working of equipments, eliminating backward production capacity, etc. Meanwhile, China should pay more attention to indirect energy savings to improve the energy utilization output benefits by increasing the added value of products, optimizing product and industry structures, and improving production technologies [63]. Secondly, advocating saving energy in everyday life is also necessary, such as providing residents with home appliances for energy savings, and enhancing the awareness of energy conservation of people, so as to ensure that people's lifestyles are changing towards more sustainable ways of living [64]. Thirdly, properly raising the price of main fossil energy resources is helpful for reducing wasted generation. Energy resources waste exists in some areas due to too low price, which is harmful for both economy and environment. Fourthly, making different price systems for main fossil energy resources at different levels so as to encourage energy saving and punish energy waste. For example, establishing an average level in one industry acts as a reference for all enterprises in this industry, these enterprises whose energy use per unit product is lower than the average level can gain low-price fossil energy resources, those ones whose energy use per unit product equals to the average level can obtain average-price fossil energy resources, and those ones whose energy use per unit product is higher than the average level are provided with high-price fossil energy resources. Similarly, this measure can be also applied to fossil energy resources consumption in everyday life through formulating average energy use per capita. Fifthly, further enhancing the share of non-carbon energy resources is necessary for $CO_2$ emission reduction, including popularizing solar energy in places where conditions permit, developing wind energy and geothermal energy in some places, promoting nuclear energy development under the prerequisite of safety, etc. Finally, the basic state policy of family planning should be enforced for each region because population growth in one region will not only significantly affect energy requirements of the region itself, but also drive up energy requirements of the other regions [65].

Here, it is needed to point out that $CO_2$ emission per capita survival can promote rational $CO_2$ emission, bring emission reduction into the framework of people's development and equal development and limited development, and then an optimal goal of emission reduction can be finally established. And it is based on human development and satisfying all population's survival and development requirements, in accord with resources supply and environmental carrying capacity. This requires that we should make clear the total $CO_2$ emission that satisfying global population's basic survival and development; meanwhile, this indicator maybe encounter many obstacles, such as resistance from some developed countries, doubt on its scientificalness and fairness and its force of constraint. Therefore, this indicator needs to be further improved in future. In addition, the indicator of living quality index is just preliminary, whose components are varying with time passes. Even so, this indicator can be applied to measure the living quality of people. Fossil energy use per unit of GDP reflects fossil energy intensity of economic activity, non-carbon energy share in energy consumption reflects the structure of energy resources, $CO_2$ emission per capita reflect the contribution of mankind's activity to $CO_2$ emission on the average, $CO_2$ emission per unit GDP reflects $CO_2$ emission intensity of economic growth, $CO_2$ emission per capita unit GDP reflects impact of economic growth and population on $CO_2$ emission, $CO_2$ emission per capita survival reflects impact of mankind's survival on $CO_2$ emission. Moreover, applying these indicators can lead to a broader understanding of the relationship among economy growth, energy consumption and $CO_2$ emission. Therefore, they can form a set of useful tool for policymakers to adjust the corresponding policies and/or take the related measures for $CO_2$ emission reduction.

## 6. Conclusion

Several indicators were applied to quantify the relationships among GDP, energy resources, and $CO_2$ emission. As an example, these indicators were applied to evaluate the comprehensive performances of China during 1990–2007.

Chinese people's living quality has been obviously improved with rapid economic growth of China but not synchronously in urban and rural areas. Fossil energy resources have been the main

driver for Chinese economic development since reformation and opening. Technical progress has been raising the energy efficiency of Chinese economy but it plays a limited role in the later period. Moreover, people's survival has an increasing contribution to $CO_2$ emission during the later period, which mainly comes from residents in urban areas. And economic scale has greater impact on $CO_2$ emission than technical progress does in this period.

Therefore, Chinese government should take comprehensive measures to control fossil energy consumption for $CO_2$ emission reduction, including saving energy in production, advocating saving energy in everyday life, properly raising the price of main fossil energy resources, making different price systems for main fossil energy resources at different levels, further enhancing the share of non-carbon energy resources, and keeping policy of family planning.

The proposed indicators can help policy-makers to take some effective measures for realizing economic growth and reducing GHGs emissions in different regions and countries.

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